Ultrafast X-Ray Sources

Workshop on New Opportunities in Ultrafast Science Using X-Rays

Napa, CA

April 14, 2002

Roger Falcone

UC Berkeley

Ultrafast x-ray sources

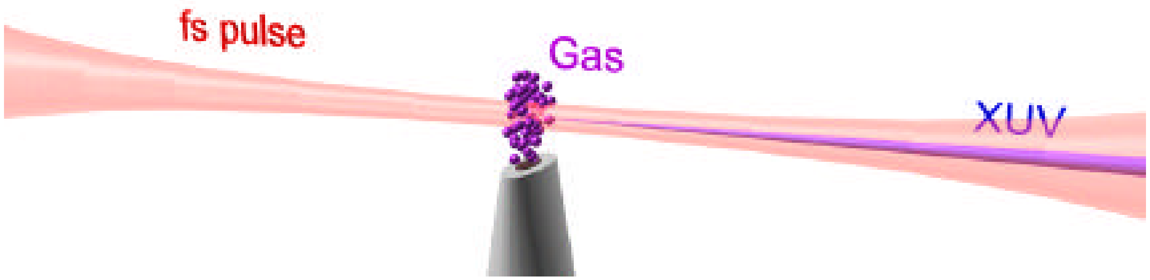
- high-order harmonics of ultrashort pulse lasers
- x-rays from laser-produced plasmas
  - x-ray tubes with laser photoelectrons
- plasma-pumped x-ray lasers
- electron storage ring synchrotrons
  - intrinsic bunching yields pulsed operation
  - ultrashort-laser slicing of electron bunches
- linear accelerator (linac) based sources
  - recirculating linacs
  - free-electron lasers
  - Thomson scattering of lasers from electrons
- ultrafast detector technologies

High-order harmonics of ultrashort pulse lasers

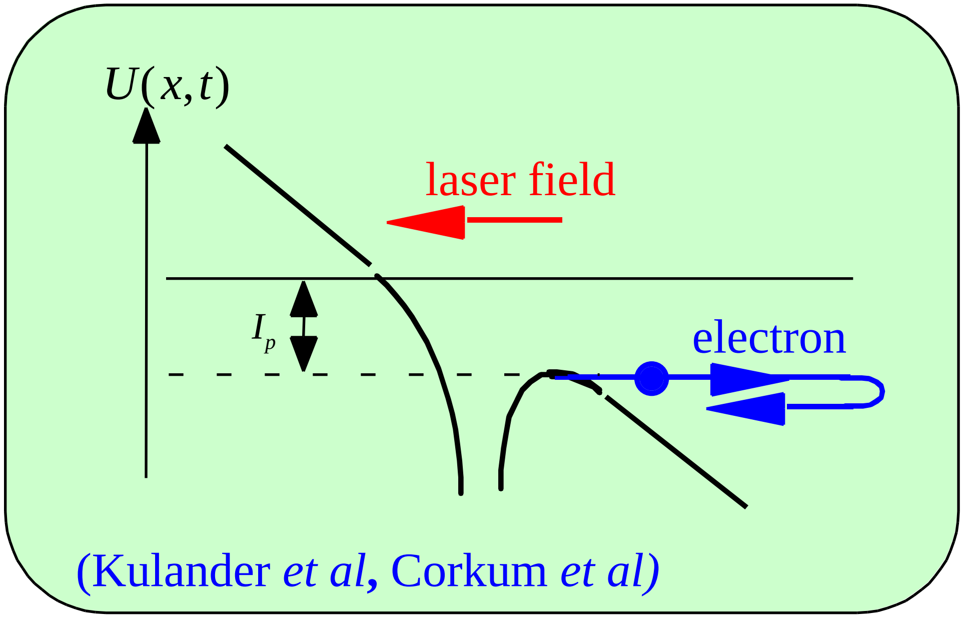
- Based on gas-filled, hollow-core fiber medium
- Typical 10^{-4} to 10^{-5} efficiency at 50 eV
- At 500 eV, 5000 photons/pulse
- Bandwidth: eV to near continuum
- Spatial coherence, angular divergence: good
- Ultrashort: 10 - 100 fs (potential sub-femtosecond pulses)
- Laser: typically 1 mJ, 1 - 10 kHz
- Details: poster from U Colorado - CXRO/LBNL

Extreme nonlinear optics: Coherent x-ray generation

- M.M Murnane, H.C. Kapteyn, *JILA*, *University of Colorado*
- *Coherent* x-rays are generated by focusing an intense laser field onto an atom
- Broad range of energies generated simultaneously from 4.5 - 600 eV
- Beam is low divergence and “laser-like”

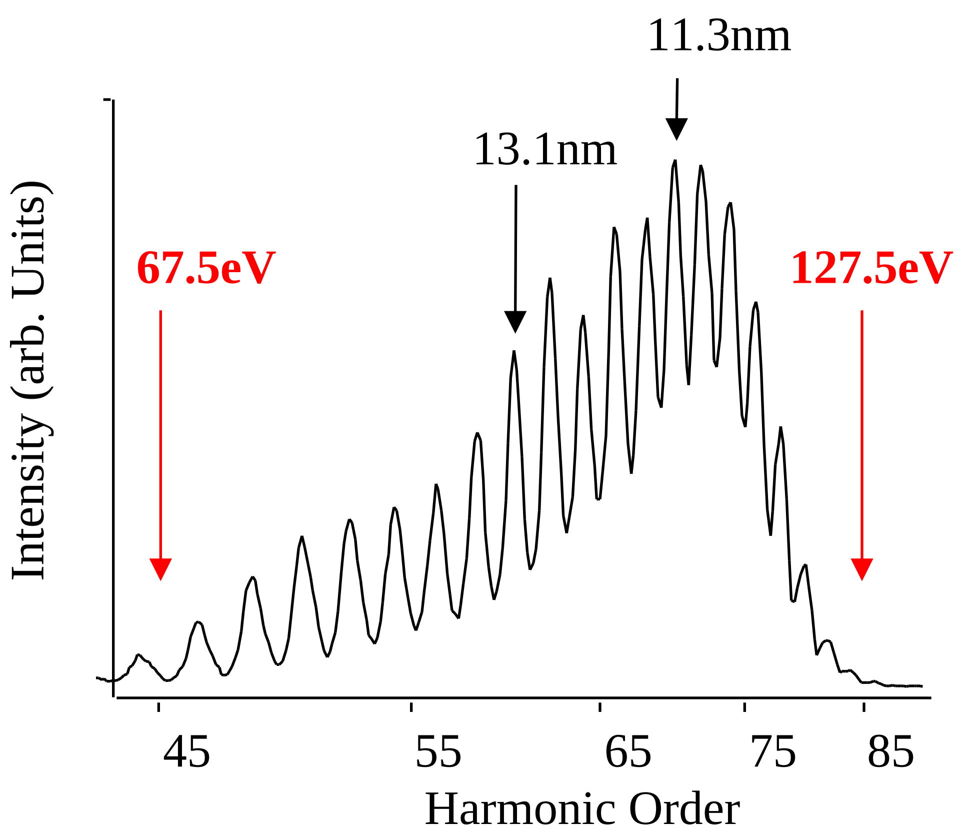


Simple picture of HHG



- **Harmonics are generated when ionized electrons recombine with an ion**
- **Phase accumulated by the electron trajectory determines the harmonic phase - many such trajectories contribute to a given harmonic**
- **The total harmonic intensity is determined by <u>interferences</u> between different trajectories from different 1/2-cycles of the laser pulse**

Typical spectrum for phase-matched HHG in helium:

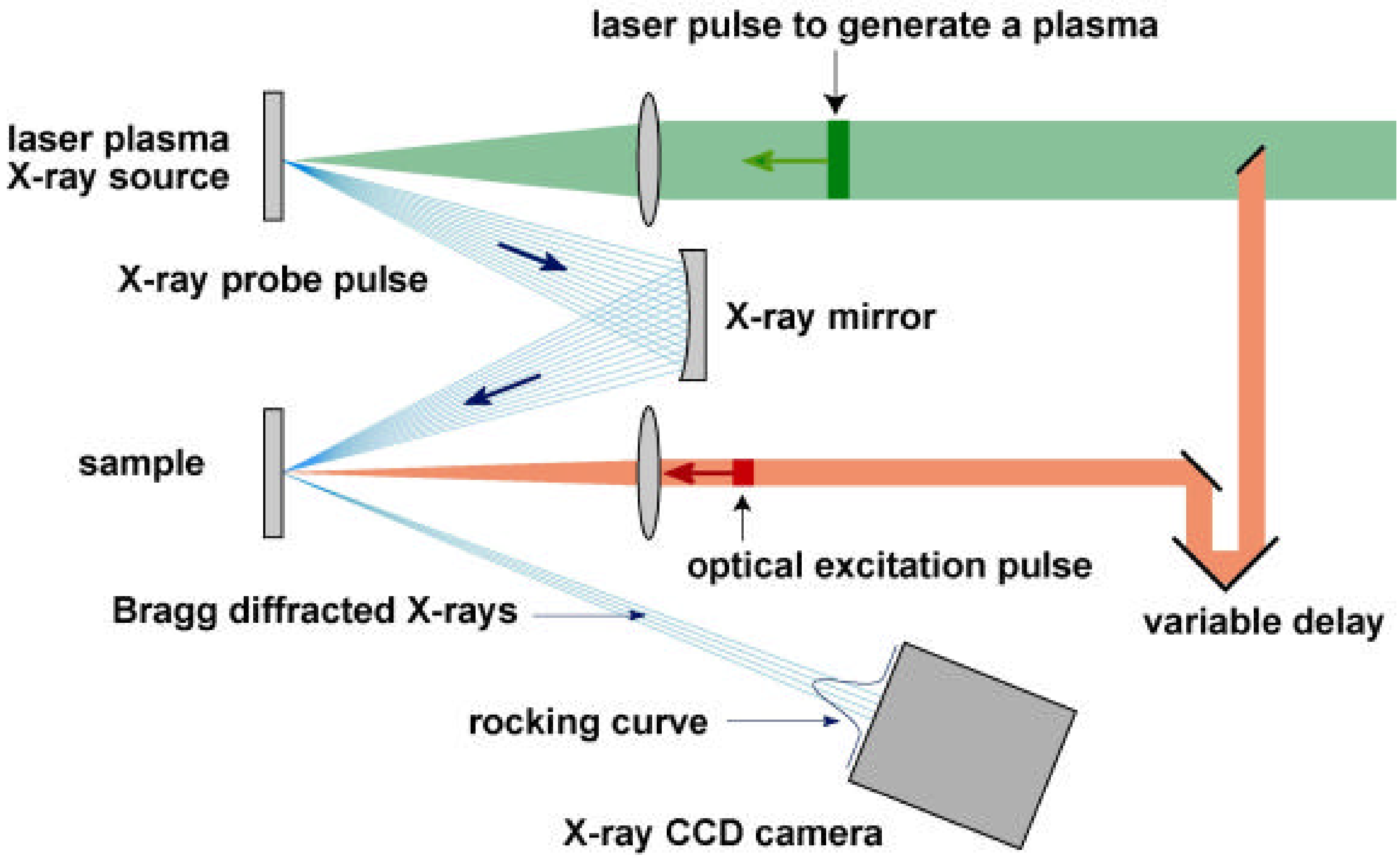


- ~10^{11} photons/sec
- Spectrum extends to ≈ 500eV under correct conditions

X-rays from laser-produced plasmas

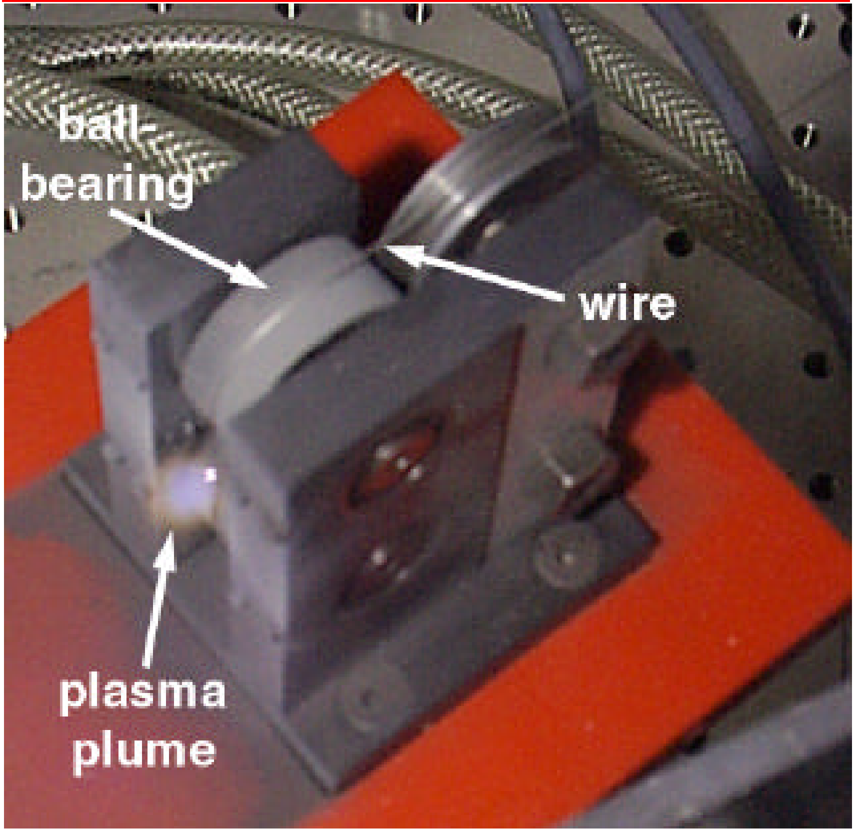
- Many labs developing small and large systems
  - diverse set of experiments; single shot vs. repetitive
  - Limited photon flux under optimized conditions
- Laser development
  - high average power and high peak power
- Debris at high average power
- Optics needed to collect large solid angle
  - broadband, single energy, focusing, etc.
- Intensity fluctuations (non-linear process)
- Pulse length < 300 fs (?)
- Spectrum
  - diffraction, absorption
- Posters: LOA/ENSTA, Brown, INRS/Quebec, Lund, Essen, etc

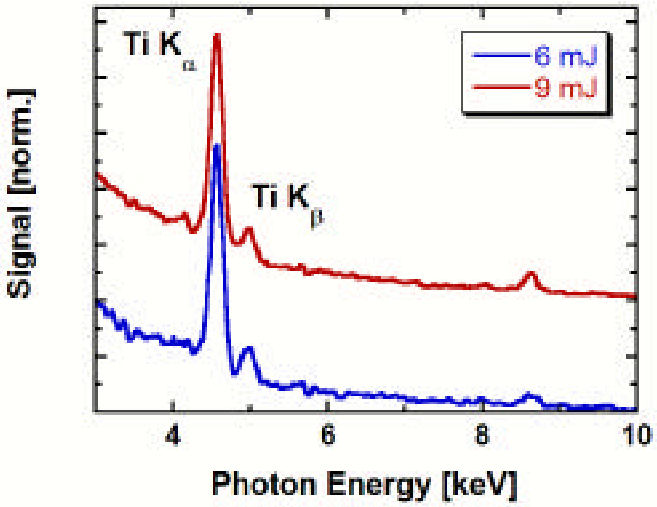
Time-Resolved X-ray Diffraction

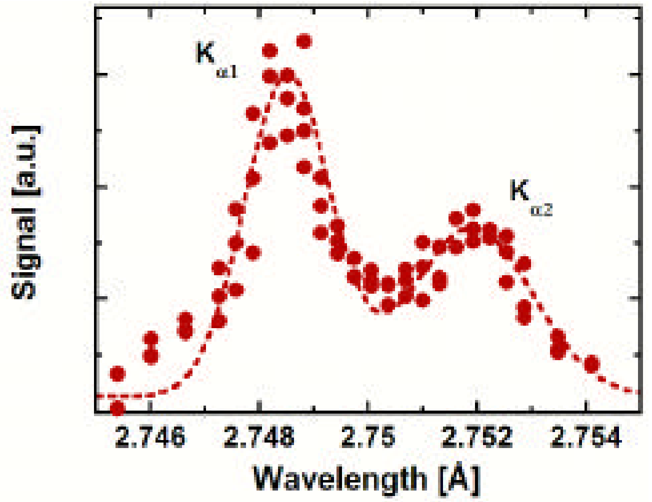


Titanium-K_α-Source at the ILP

Laser: Ti:Sa, **120 fs, 150 mJ**
Target: moving **Ti-wire**





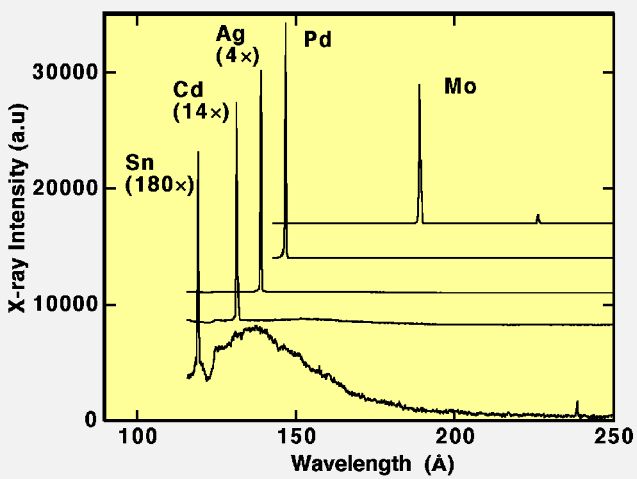


Plasma-pumped x-ray lasers

Laser driven collisional x-ray lasers have high brightness: Summary of COMET x-ray laser characteristics

- X-ray laser pulses in the energy range 25 - 104 eV are generated by two laser beams from the COMET table-top laser
- This may be extended to higher energies of 150 eV

Ni-like ion x-ray laser lines: Mo, Pd, Ag, Cd, Sn



X-ray Laser Beam Parameters

Energy:	25 – 104 eV
Bandwidth:	$\Delta\lambda/\lambda < 10^{-4}$
Output Energy:	>12 μJ
Photons/pulse:	$>10^{12}$
Divergence:	1 – 3 mrad × 5 – 10 mrad (H × V)
Source Size:	20 – 50 μm × 80 – 130 μm (H × V)
Pulse Duration:	2 – 7 ps (FWHM)
Shot Rate:	1/ 4 minutes
Brightness:	$5 - 17 \times 10^{24}$ ph mm^{-2} mrad^{-2} s^{-1} (0.01% BW)$^{-1}$

Main advantages of the x-ray laser beam are the properties of high photon flux, picosecond pulse and narrow energy bandwidth

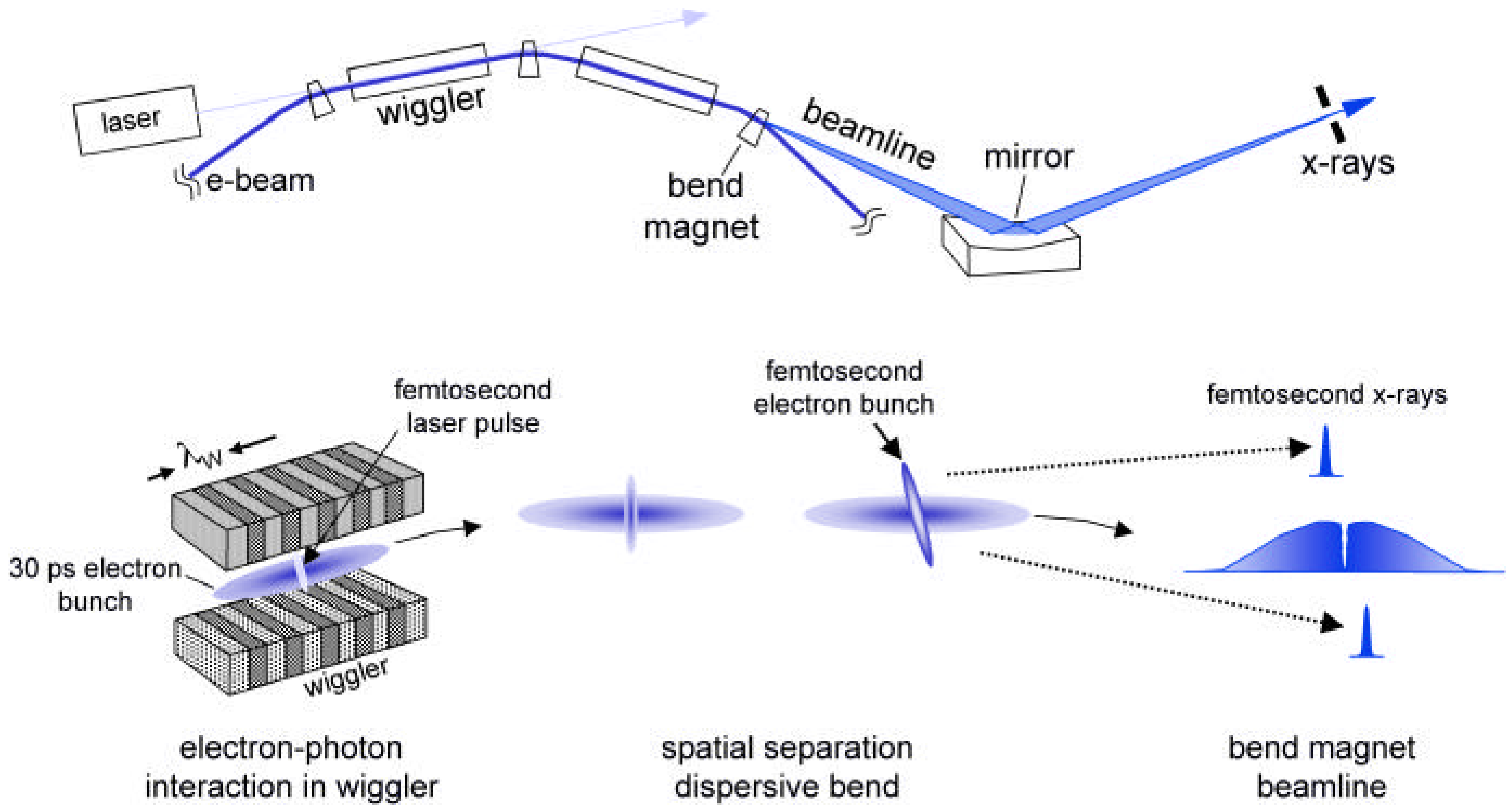
3rd generation storage ring synchrotrons

- Use 100 ps synchrotron pulses from current synchrotron sources
- Nanosecond gated detectors allow single pulse detection and pump/probe experiments to prepare for 4th generation
- Slicing sources implemented on 3rd generation sources
  - LBNL
  - proposed laser controlled scattering switches
    - LBNL, APS
  - Use of ultrafast detectors
- Extensive work represented in Posters:
  - ESRF/Grenoble, APS/Argonne, ALS/Berkeley/LBNL, MBI/Berlin

Laser slicing of electron bunches in storage rings

- Pulse length
  - Dispersion limited (SLS uses one straight section for 80 fs)
  - 100 fs - 200 fs
- Signal-to-background (intrinsic 100 fs / 100 ps ratio)
  - Electron density off-axis
  - Mirror quality (not previously important)
  - Currently 1:1 sufficient (use differential measurements)
- Repetition rate
  - Laser development needed to bring to 100 kHz
- Synchronism of laser/x-rays good
- Want unity-QE detectors with 100-ns gating
- Posters from LBNL, SLS, BESSY II
  - Spectroscopy and diffraction: from to multiple keV

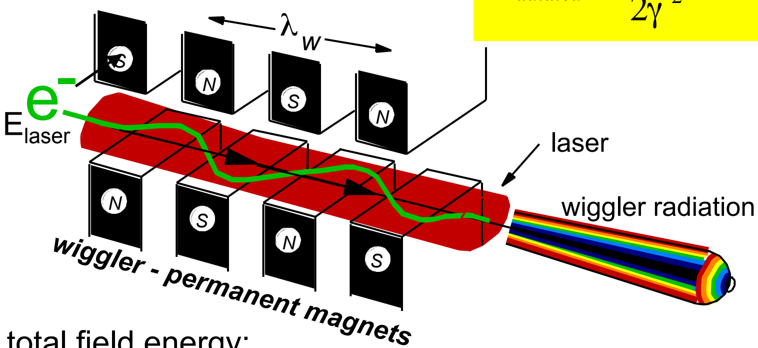
Generation of Femtosecond X-rays from the ALS



Zholents and Zolotorev, *Phys. Rev. Lett.*, **76**, 916,1996.

Energy Modulation in the Wiggler

$$\lambda_{radiated} = \frac{\lambda_w}{2\gamma^2}(1+K^2/2) = \lambda_{laser}$$



total field energy:

$$A \sim \int \left|E_L(\omega,\vec{r}) + E_R(\omega,\vec{r})\right|^2 dS d\omega = A_L + A_R + \underbrace{2\sqrt{A_L A_R \frac{\Delta\omega_L}{\Delta\omega_R}}\cos\phi}_{\Delta E \text{ (energy mod)}}$$

wiggler radiated energy:

$$A_R \quad \pi\alpha\hbar\omega_R \frac{K^2/2}{(1+K^2/2)}$$

Laser requirements:

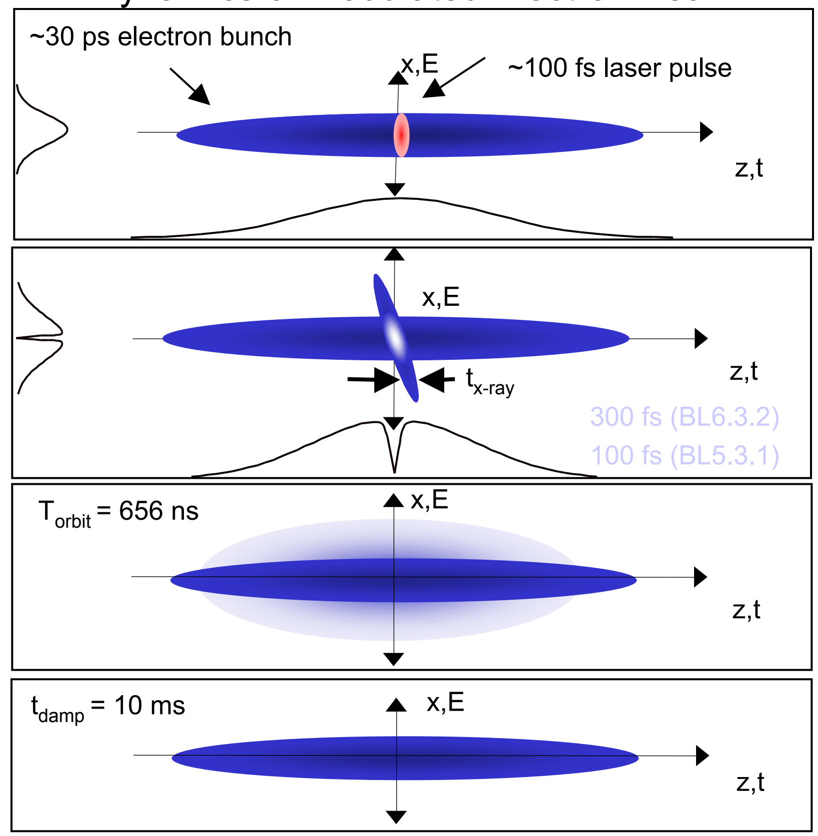
$\omega_L = 1.55$ eV

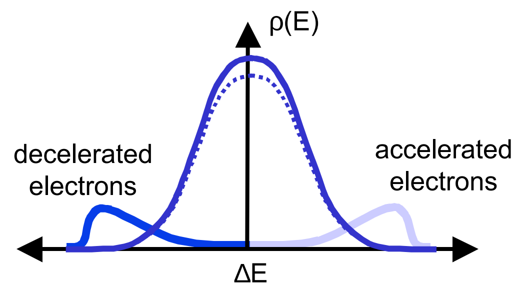
$\Delta\omega_L = 19$ period wiggler   25 fs laser pulse $\boxed{\Delta E \quad 9 \text{ MeV}}$

$A_L = 100$ μJ

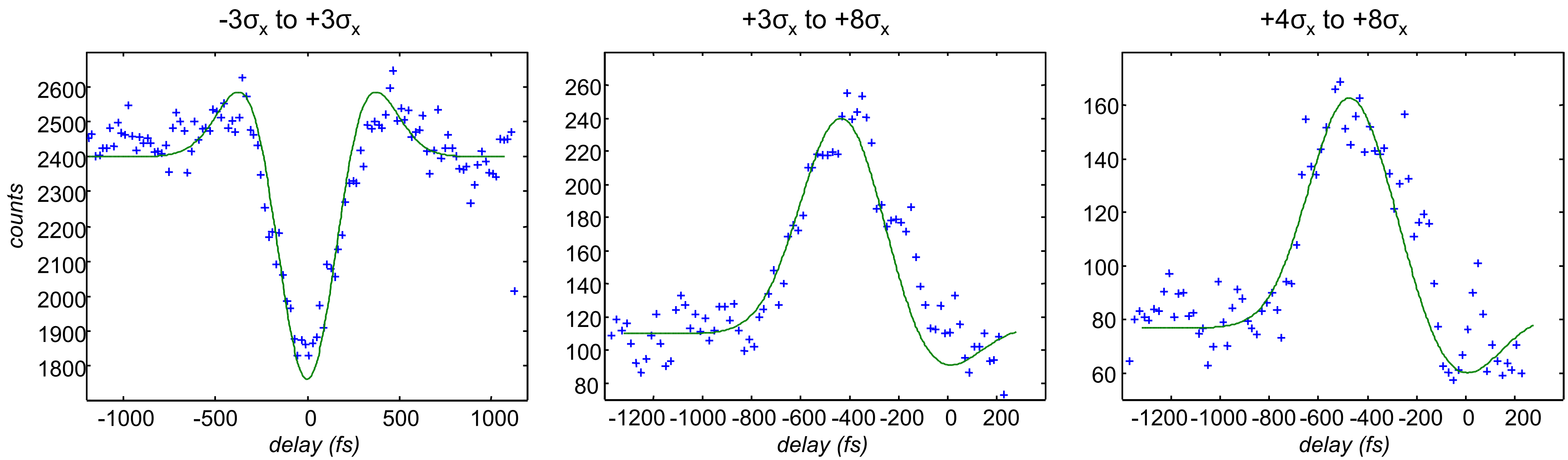
ALS beam energy spread σ_E ~1.8 MeV E_o =1.9 GeV

Dynamics of Modulated Electron Beam

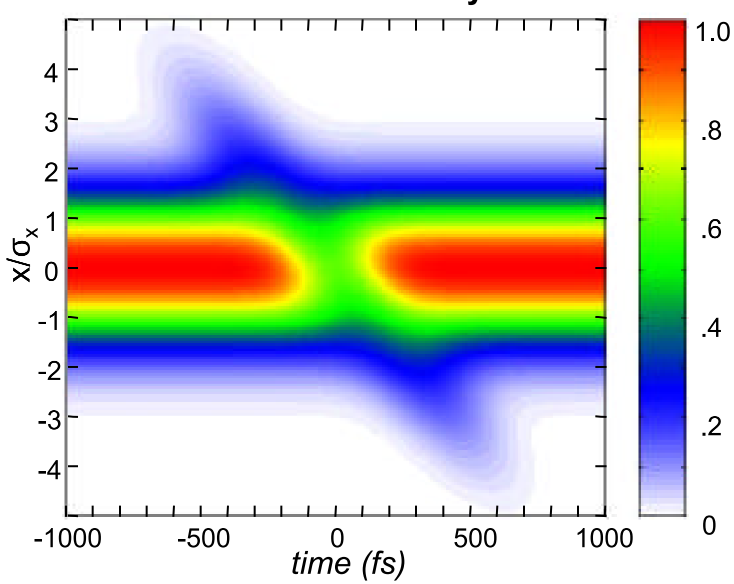


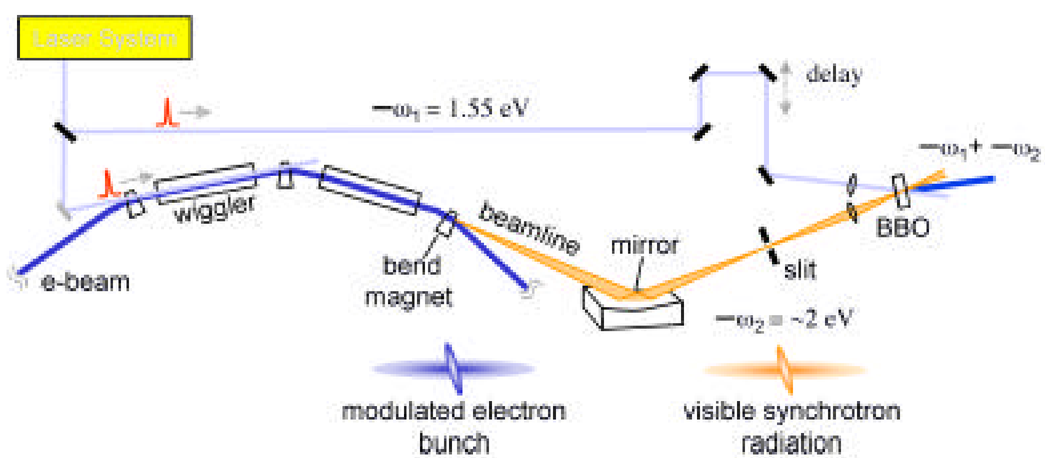


Femtosecond Pulses of Synchrotron Radiation



Calculated Electron Density Distribution





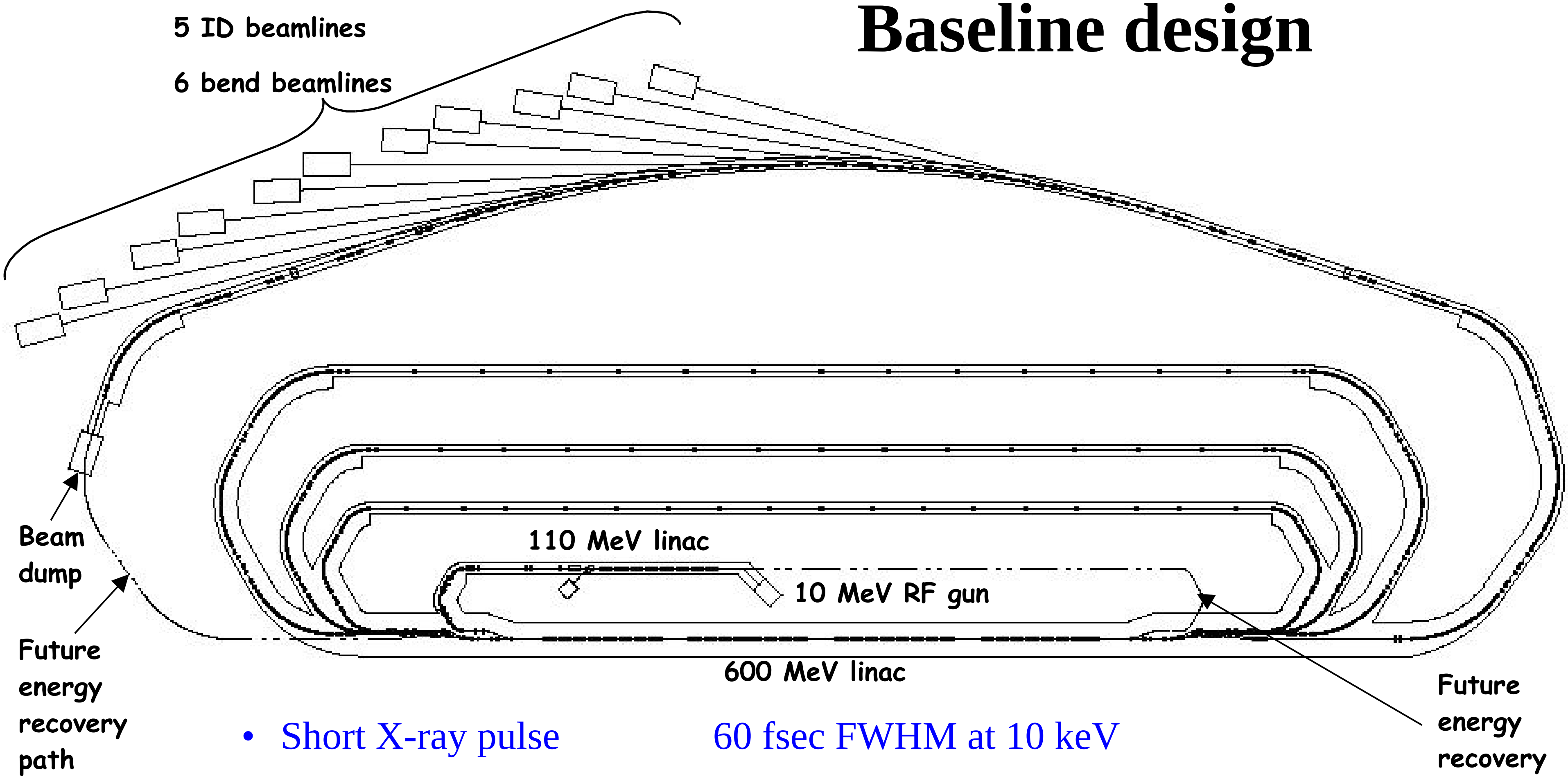
Schoenlein et al., *Science*, **287**, 2237 (2000)

Linacs: recirculating - energy recovery

- High repetition rate (10’s Hz, to 10 kHz, to multi-mega-Hz)
- Flux performance comparable to synchrotrons; with ultrashort pulses
- Expect 100 fs or less pulses
  - Needs development
    - Photocathode
    - Electron and optical pulse compression schemes
    - Synchronization issues (crab cavity designs); coherent synchrotron emission
- Take advantage of superconducting accelerator technology
- Possible energy recovery
- Synchrotron user mode
  - multiple ports; undulator, wigglers
- Availability (?) near-term, long-term
- Posters: ERS/CHESS, RLS/LBNL, SPPS/SLAC

An ultra-fast x-ray source for fsec dynamics

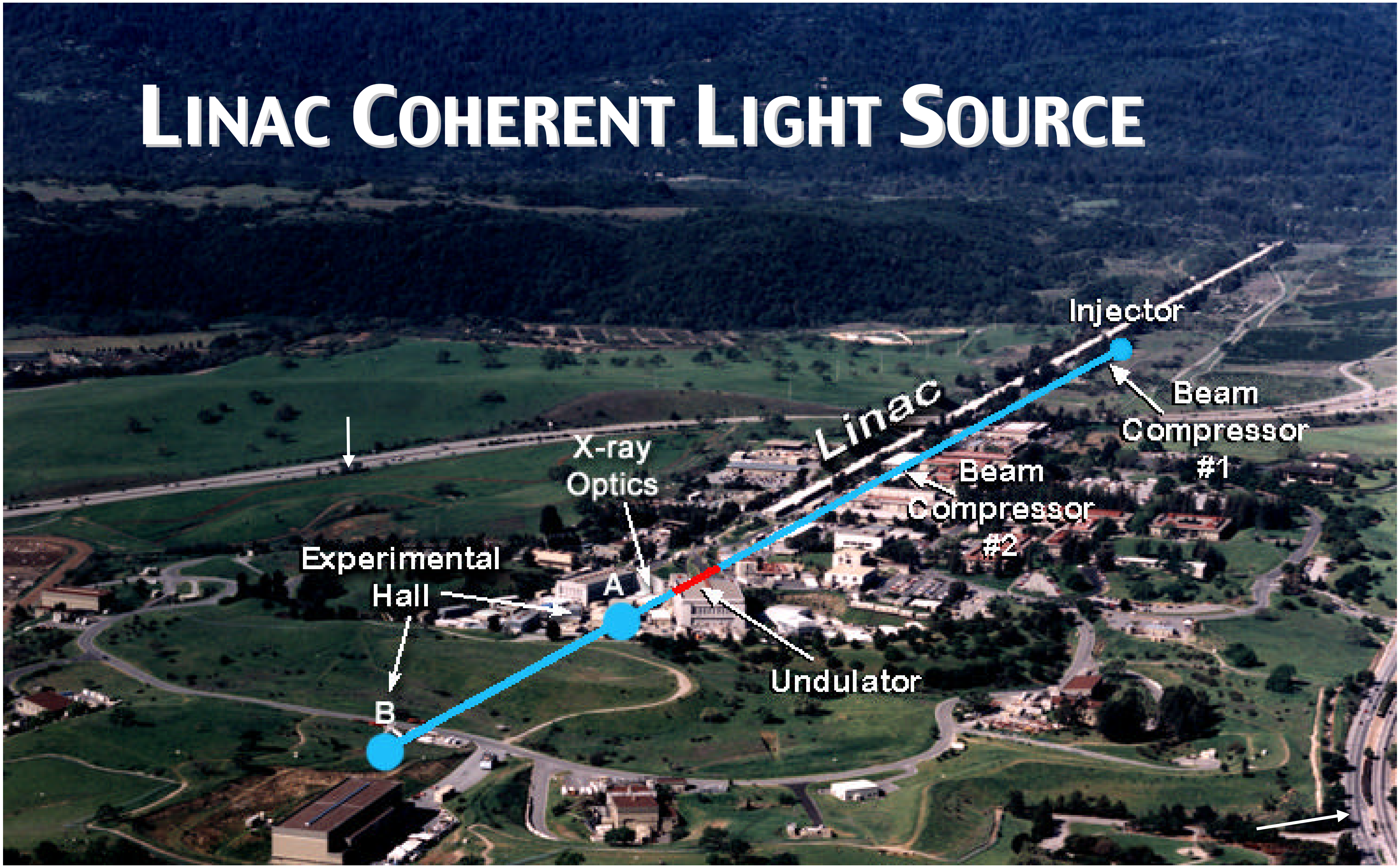
Baseline design



- Short X-ray pulse — 60 fsec FWHM at 10 keV
- High repetition rate — 10 kHz
- High flux — 3.4x1010 photons/sec/0.1%BW at 10 keV
- Tunable — 1-12 keV

Free electron lasers

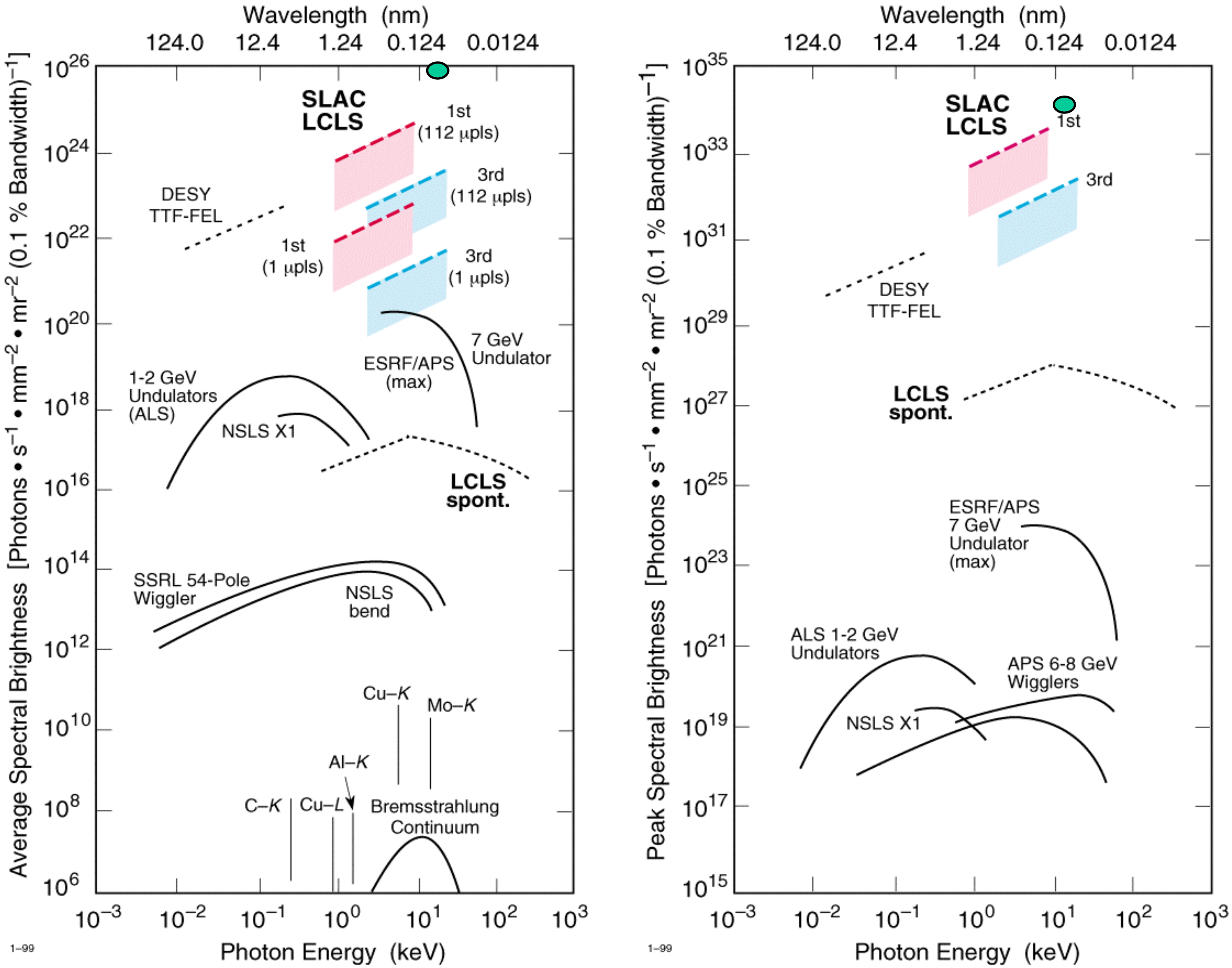
- Highest per pulse ultrafast x-ray source
- 100 Hz repetition rate
- Challenges
  - Energy and power handling
    - Sample damage
  - Multiuser availability
  - technology scaling (10 eV to 200 eV to 10 keV)
  - pulse length 200 fs to 10 fs (?)
  - Synchronization: better than 10 ps (?)
    - absolute or shot by shot
- narrowband pulse / broadband spontaneous background
- Posters: LCLS/SLAC, TESLA/DESY, 4GLS/Darebury

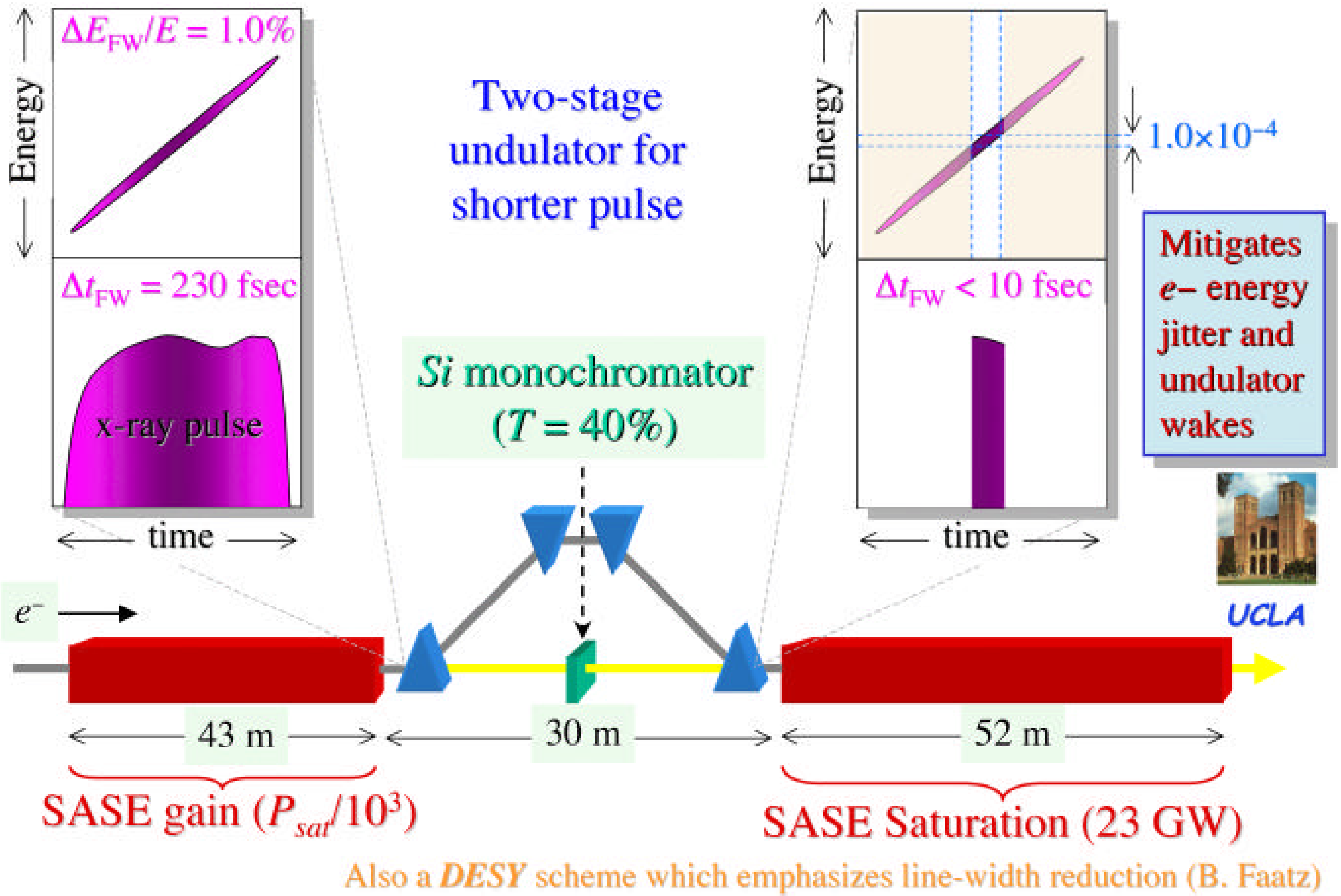

LINAC COHERENT LIGHT SOURCE
Injector
Linac
Beam
Compressor
#1
Beam
Compressor
#2
X-ray
Optics
Experimental
Hall
A
B
Undulator

Performance Characteristics of the LCLS

Peak and time averaged brightness of the LCLS and other facilities operating or under construction

~ TESLA Performance



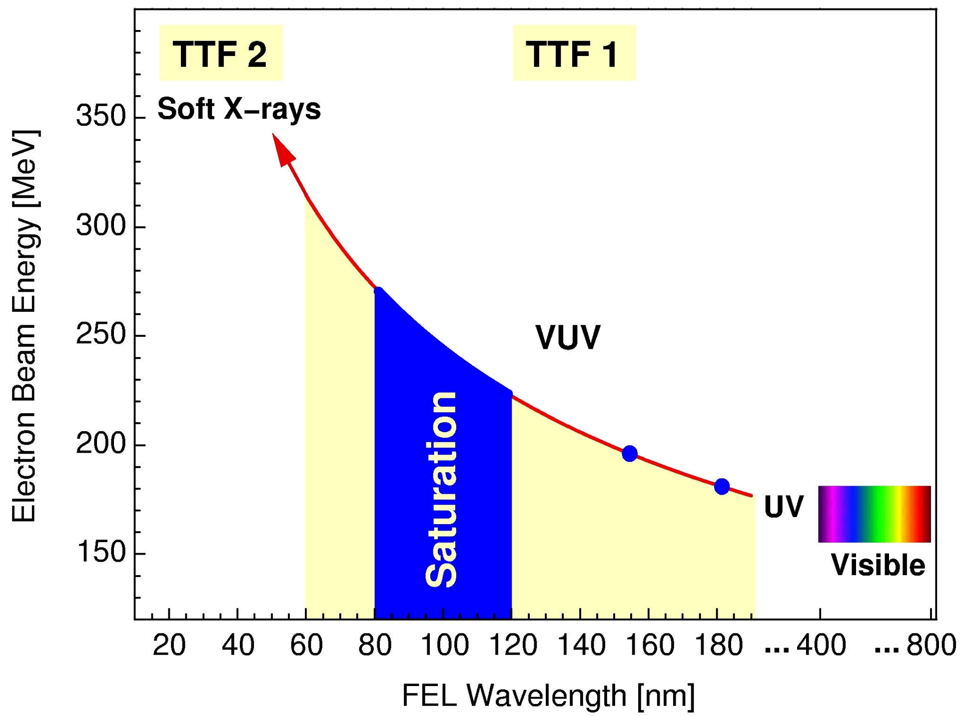


$\Delta E_{FW}/E = 1.0\%$
Energy
$\Delta t_{FW} = 230$ fsec
x-ray pulse
time
Two-stage
undulator for
shorter pulse
Si monochromator
($T = 40\%$)
Energy
1.0×10^{-4}
$\Delta t_{FW} < 10$ fsec
time
Mitigates
e– energy
jitter and
undulator
wakes
UCLA
e^-
43 m
30 m
52 m
SASE gain ($P_{sat}/10^3$)
SASE Saturation (23 GW)
Also a ***DESY*** scheme which emphasizes line-width reduction (B. Faatz)

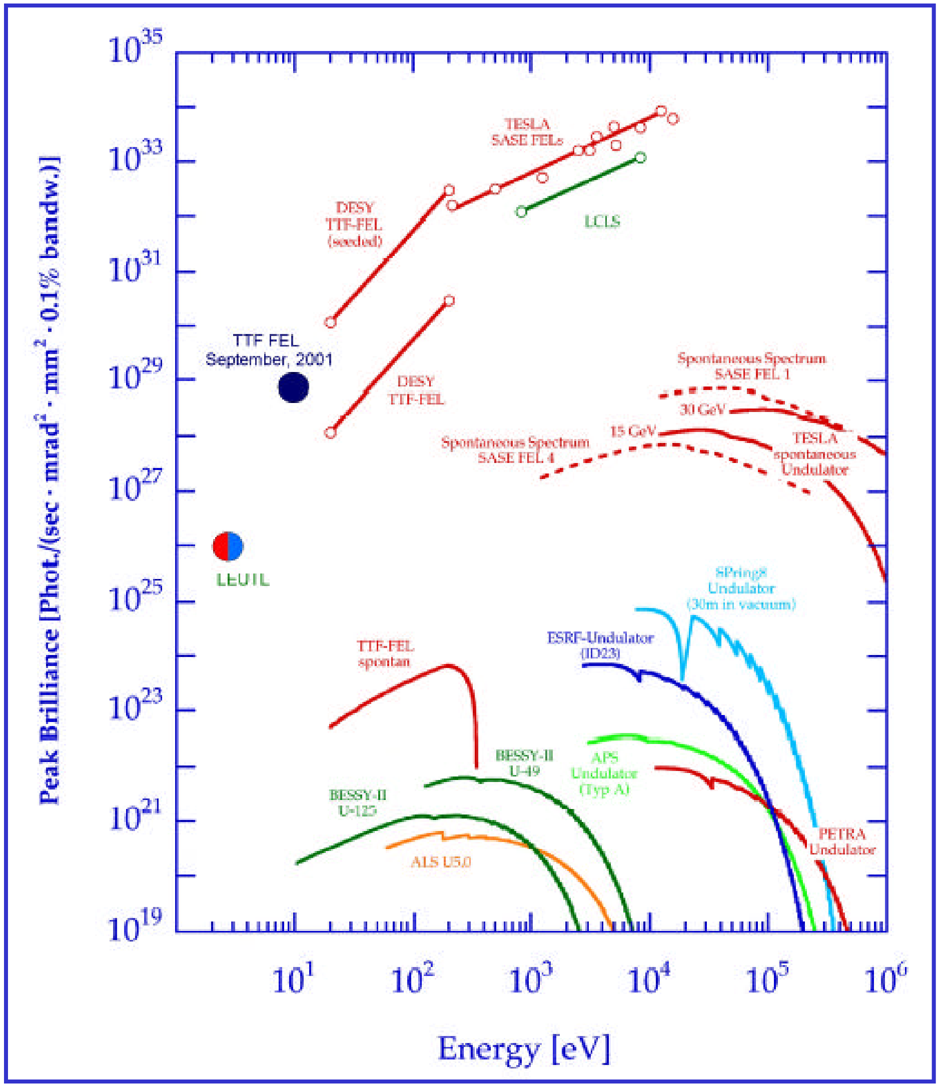
Present status TTF VUV-FEL

Key parameters TTF experiments

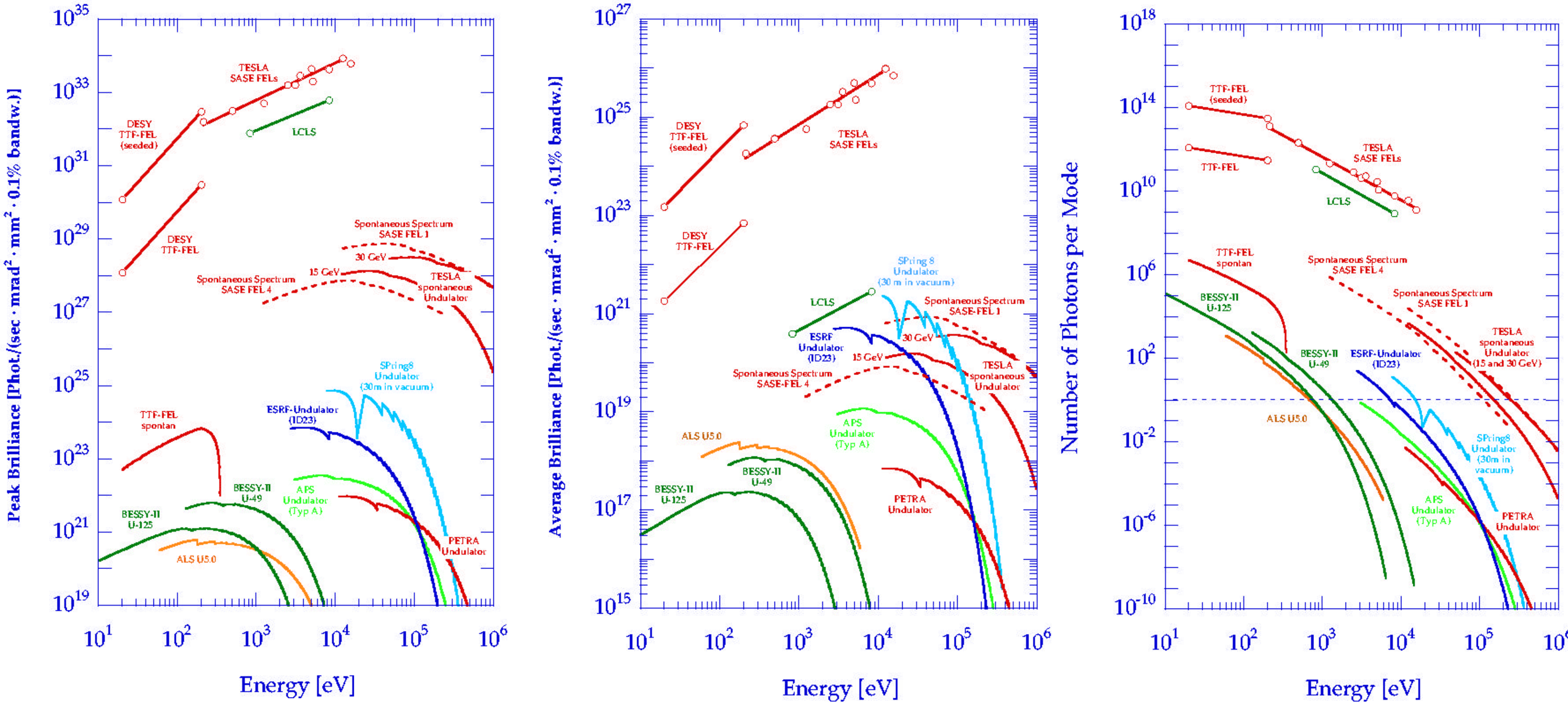
wavelength	95-105 nm
pulse energy	30-100 µJ
pulse duration	30-100 fs
peak power	1 GW
source size	200µm
beam divergence	260 µrad
peak brilliance	10^{29}
photons per pulse	10^{14}



Present status TTF VUV-FEL



TDR for TESLA XFEL

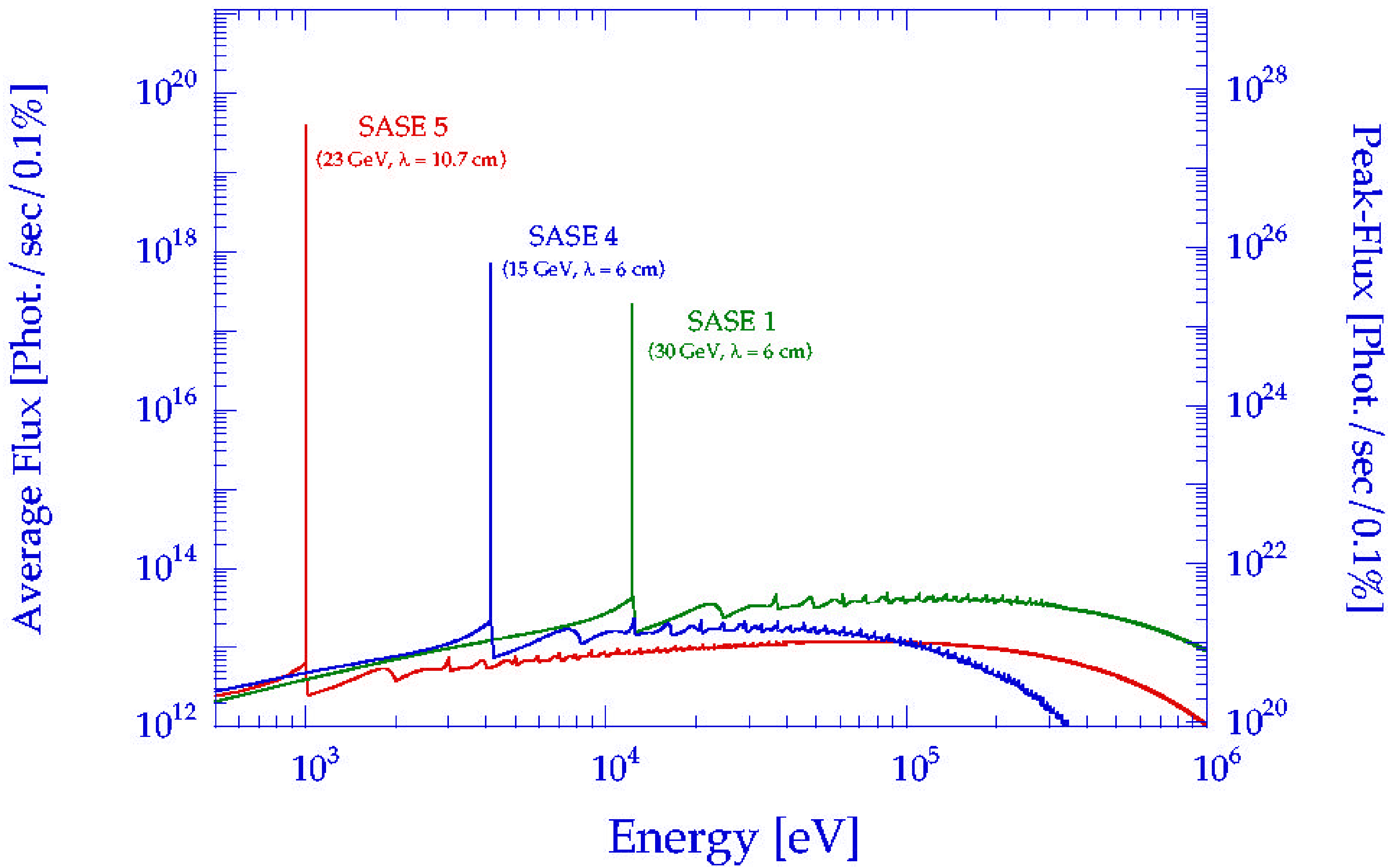


Parameters for TESLA XFEL

TESLA XFEL (pulse duration 100 fs, 10 hz x 11500 pulses)

	units	0.1 nm	0.25 nm	0.4 nm	1.0 nm	2.5 nm
peak brilliance	phts/ s mm^2 $mrad^2$ 0.1%	8.7e33	4.4e33	1.8e33	9.3e32	3.6e32
photons/mode	#	7.2e09	5.7e10	9.6e10	7.7e11	4.7e12
peak power	GW	37	65	110	185	240
energy/pulse	mJ	3.5	6.4	9.6	18.0	23.8
beam size	µm	100	100	60	68	71
divergence	µrad	0.8	1.9	3.3	6.4	11
bandwidth	%	0.08	0.12	0.3	0.4	0.54
trans. coh.	mm	0.8	1.3	1.6	3.2	5.5
long. coh.	nm	125	210	130	250	460

TDR for TESLA XFEL



Proposed xFEL-based light sources

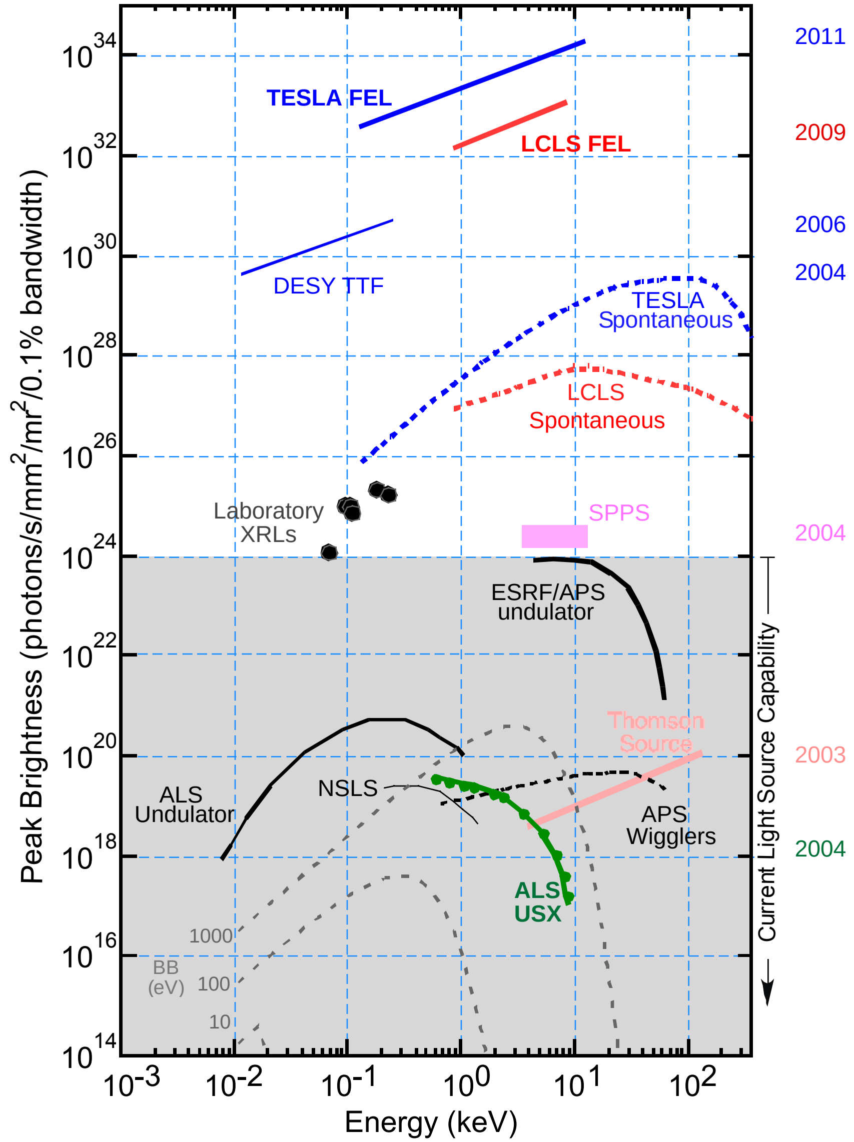
	LXRL (5.9 nm)	TTF (6.0 nm)	LCLS (0.1 nm)	TESLA (0.1 nm)
mJ/pulse	0.3	0.3	2.6	3.7
Photons/pulse	$9x10^{12}$	$9x10^{12}$	$2x10^{12}$	$2x10^{13}$
Pulse Length (fs)	10^{5}	10^{2}	$2x10^{2}$	10^{2}
GW	.006	3	26	37
Peak Brightness	$1.8x10^{25}$	$2.0x10^{30}$	$1.2x10^{33}$	$8.7x10^{33}$
Bandwidth (%)	0.01	0.6	0.3	0.1
Hz	< 1	50	100	50
Date	now	2004	2008	2011

Next generation of light sources may be LINAC-based: *tunable x-ray lasers*

- Previous light sources are synchrotron radiation based
  - Circular machines
  - High duty cycle (> MHz)
  - Tunable over wide energy ranges
  - Low # of electrons and photons per bunch
  - Long bunch duration (~ 50 ps)

- Next generation: LINAC based
  - Short bunch duration (~100 fs)
  - Full transverse coherence
  - Low repetition rate (~100 Hz)
  - Tunable
  - High peak brightness

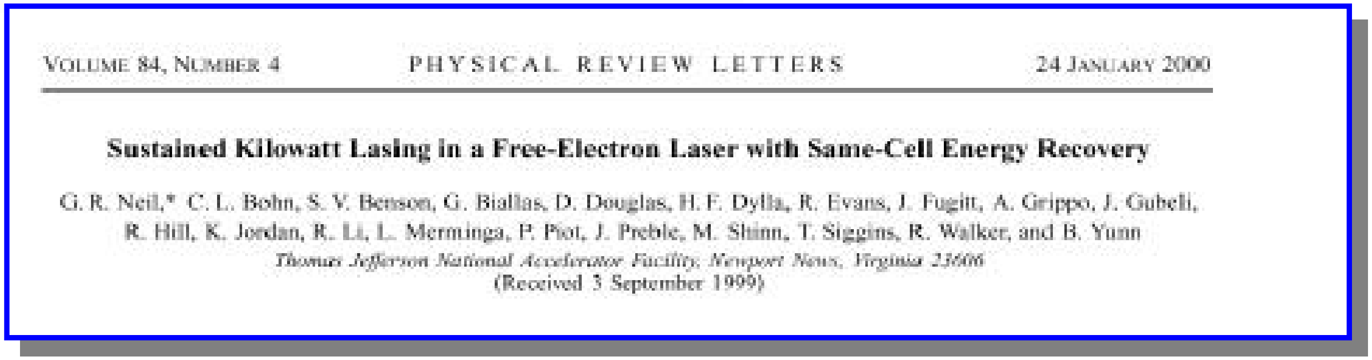
- ***Open new possibilities for plasma related studies***



Thomson scattering from linacs

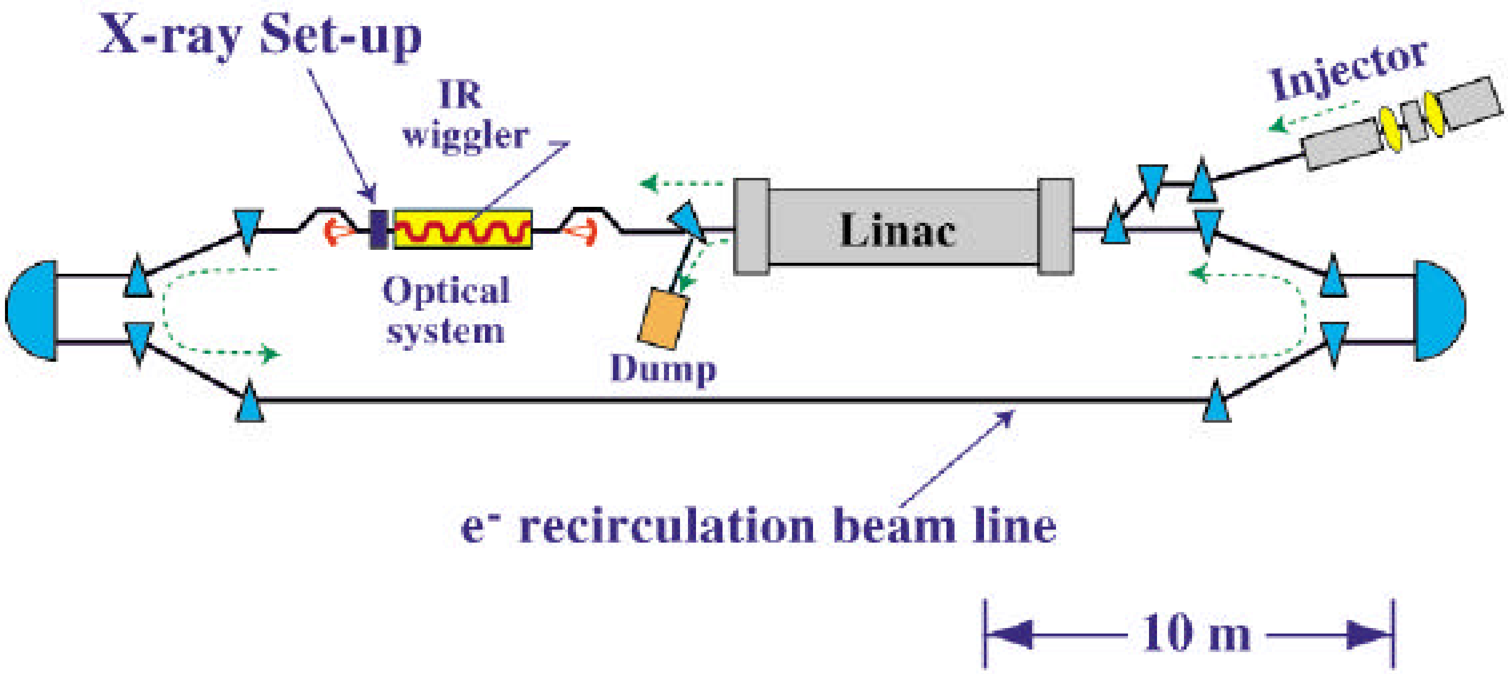
- Short pulse laser scatter off intense electron beams
  - demonstrated technology
- Potential high average power (Duke ir-FEL) at multi-megaHz rep.
- Potential high peak power (LLNL)
- Challenges
  - Electron phase space limits
    - Spectrum (shifts to short wavelength at high electron energies)
    - Emission angle (broadens at highly focused electron beams)
    - Pulse length (limited by interaction volume)
    - Saturation at relativistic laser intensities
- Posters (FEL Lab/Duke, PLEIADES/LLNL)

Jefferson Lab ERL layout


VOLUME 84, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JANUARY 2000

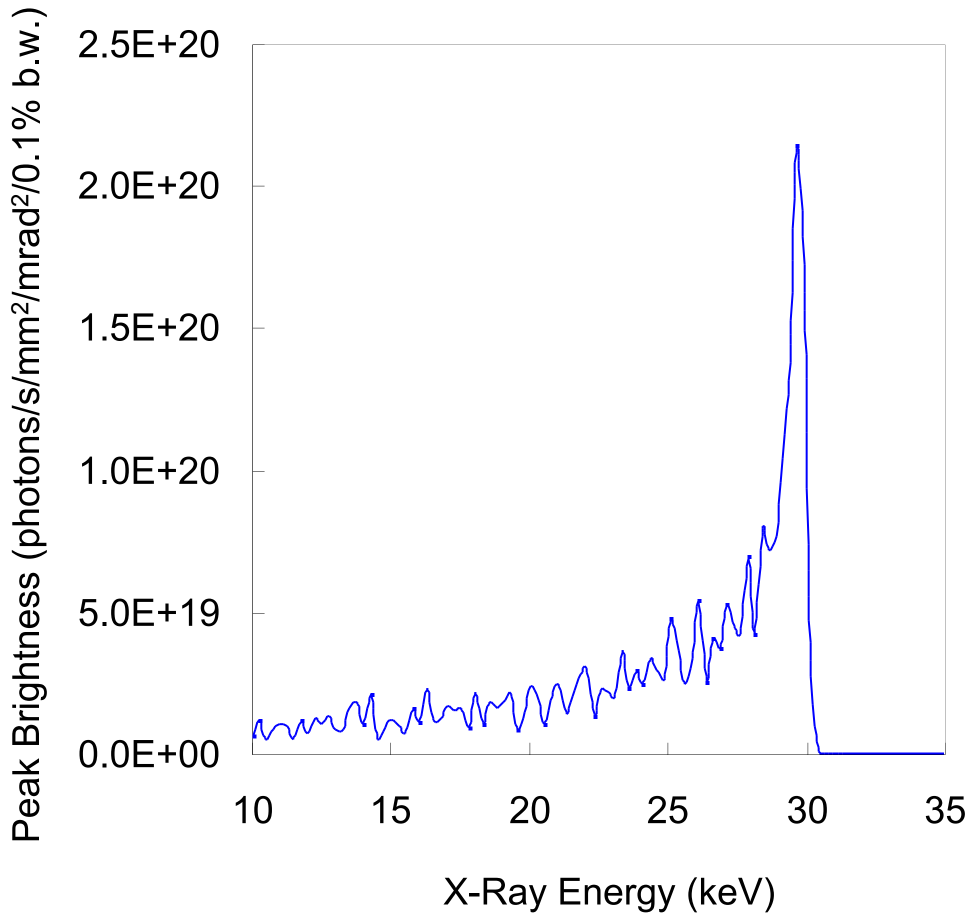
Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery

G. R. Neil,* C. L. Bohn, S. V. Benson, G. Biallas, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, A. Grippo, J. Gubeli, R. Hill, K. Jordan, R. Li, L. Merminga, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
(Received 3 September 1999)



3D Frequency-Domain Code:

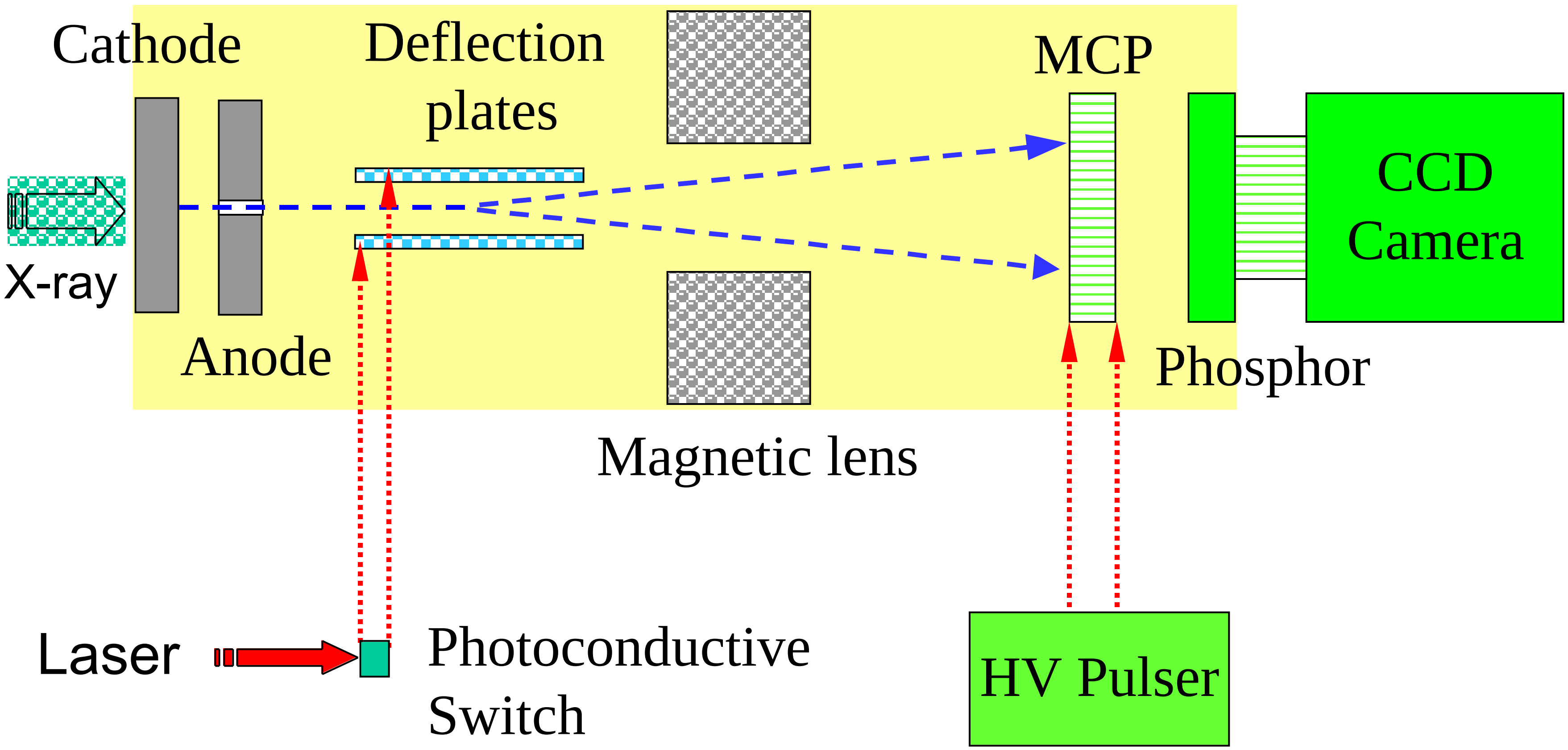
35 MeV, 0.5 nC, SQs, 2m-drift
300 mJ, 100 fs, 10 μm radius, A^2 = 0.25



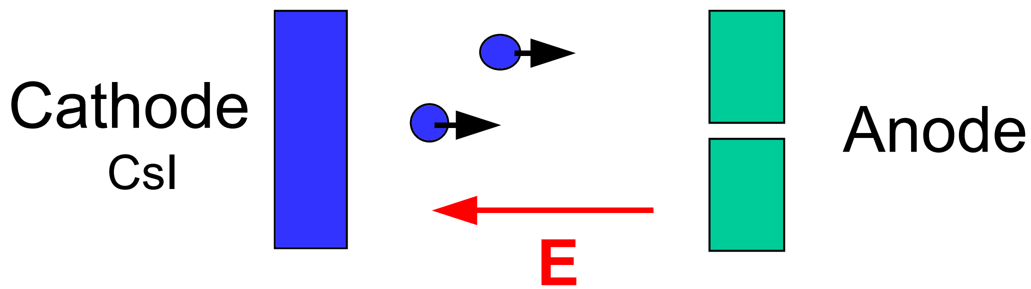
Fast Detectors

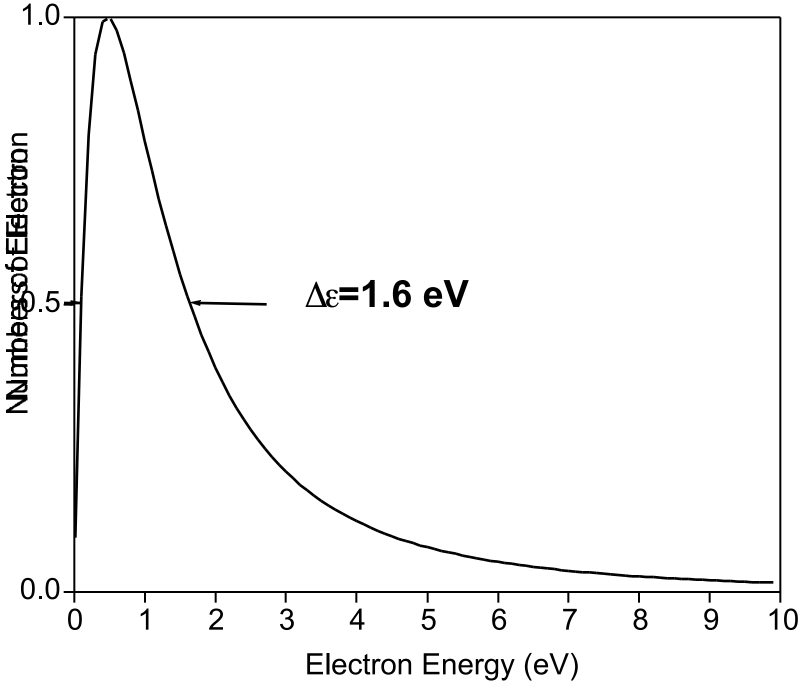
- Ultrafast x-ray cameras
  - Development effort for 100 fs resolution
  - Complete record of 100 ps behavior
- X-ray / short pulse laser cross-correlation techniques
  - LBNL, APS/Michigan
- Compton scatter
  - Chirped laser with spatial resolution
- Posters: Berkeley/LBNL, SPPS/SLAC

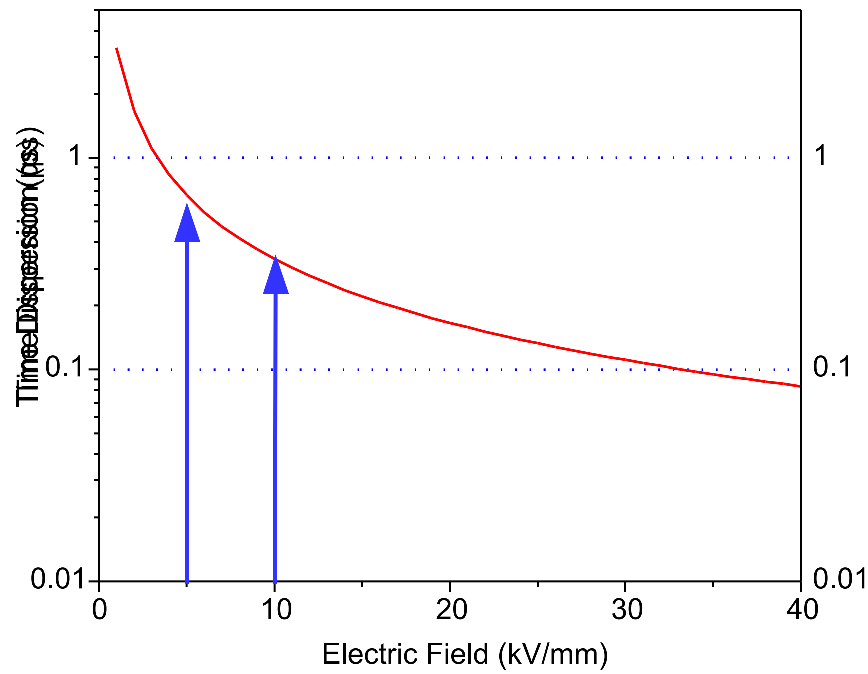
Sub-ps X-ray Streak Camera



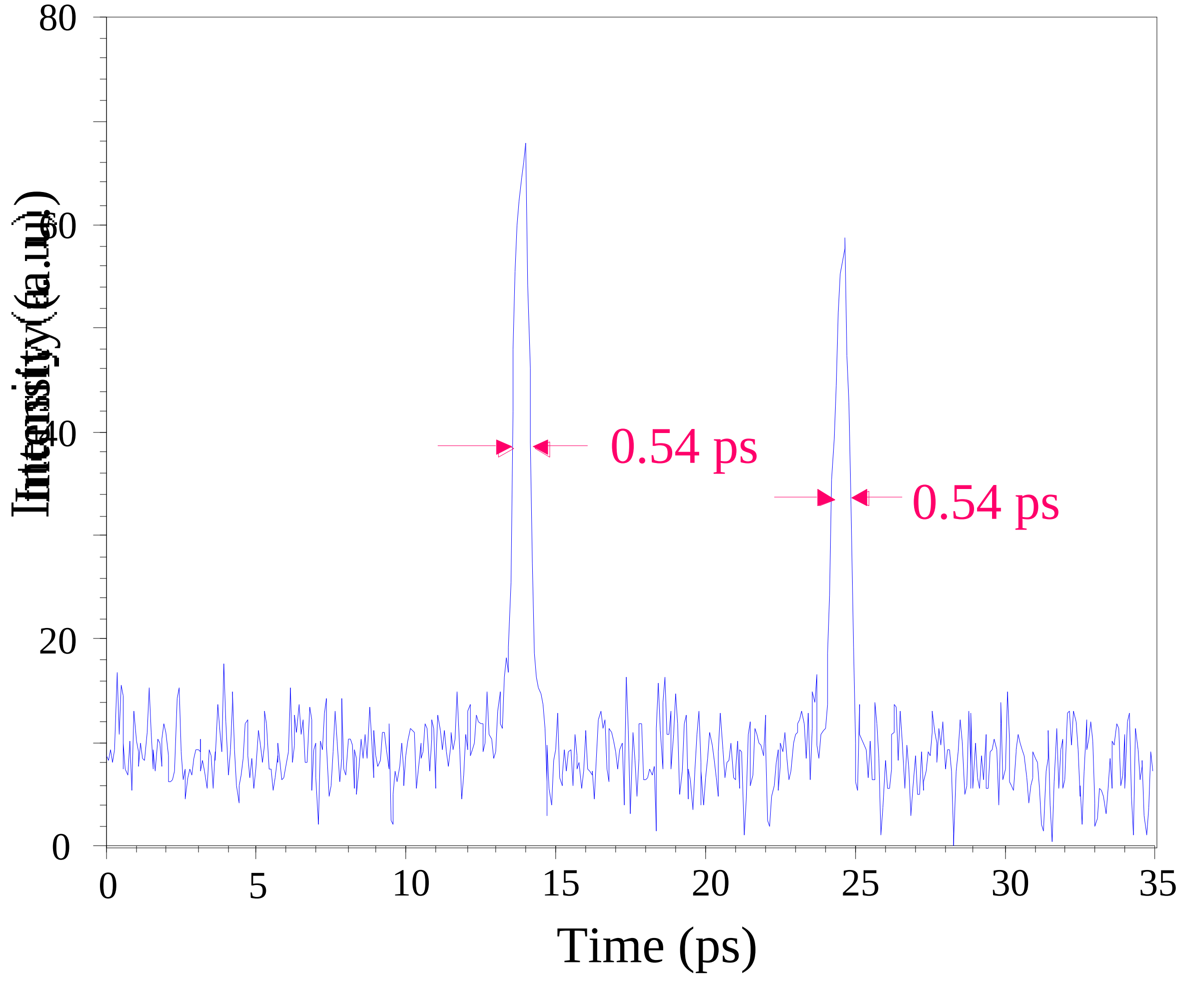
Temporal Dispersion



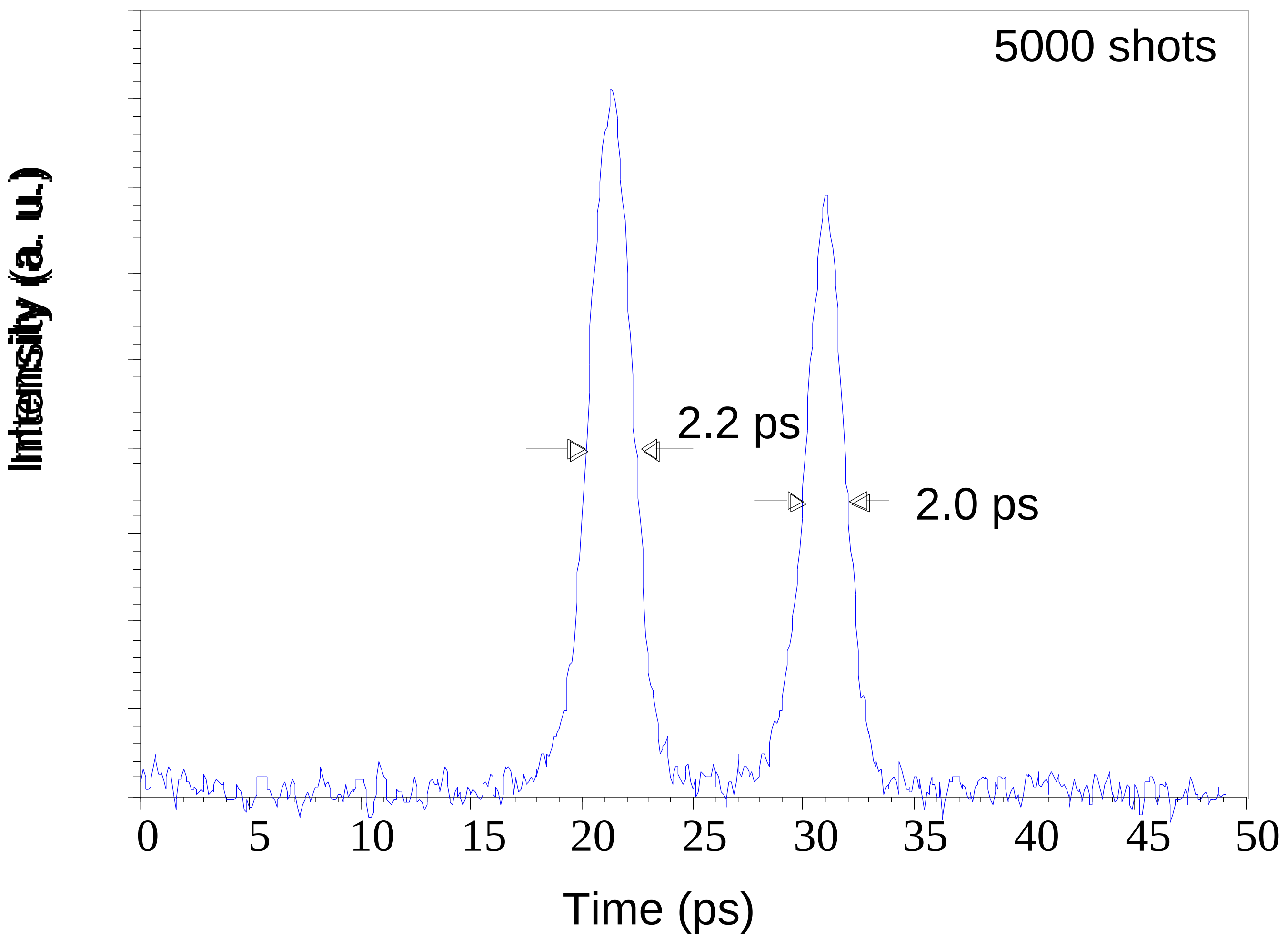




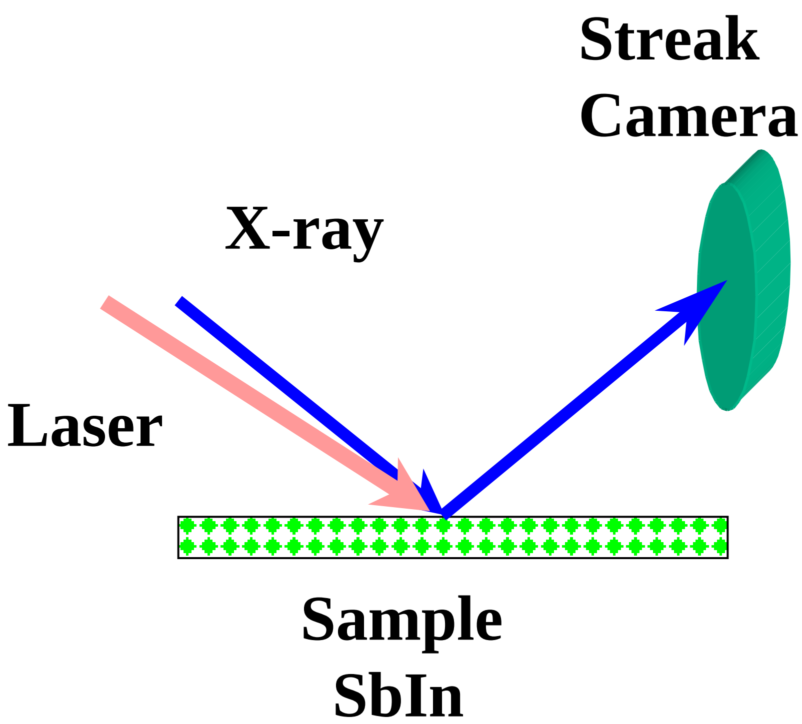
Single Shot Resolution

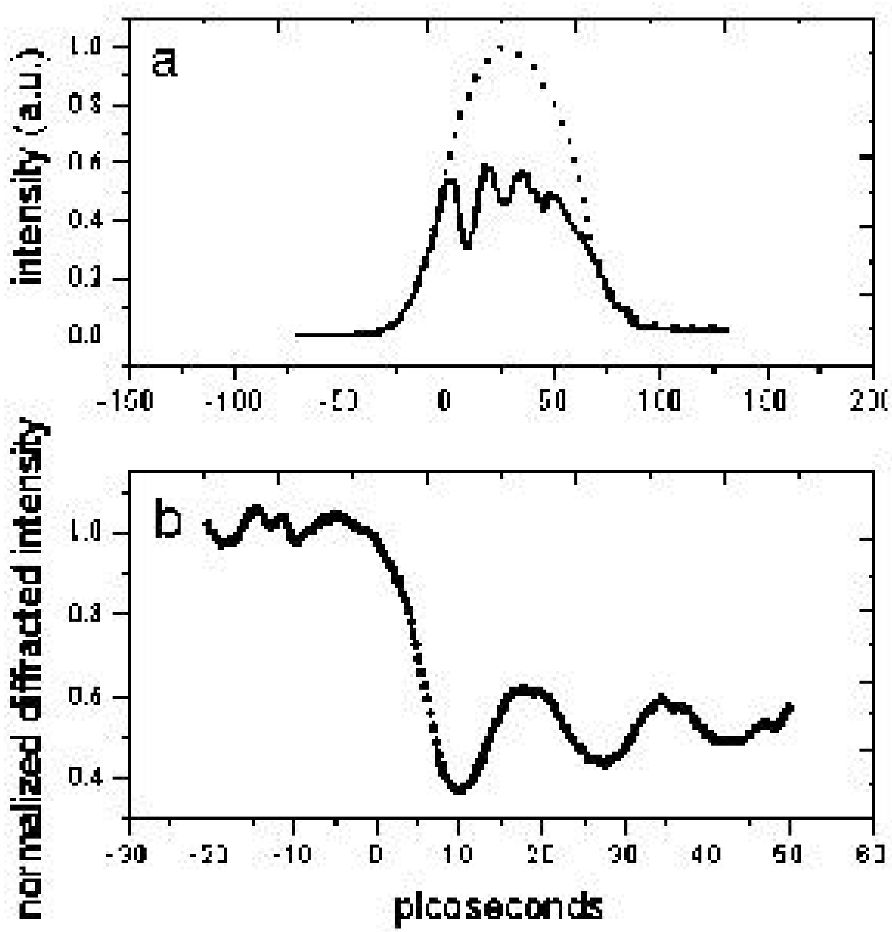


Jitter Limited Resolution



Time-Resolved Diffraction





Overall Issues/Challenges

- Experiments in ultrafast x-ray science place special requirements on sources and infrastructure
  - Will hear those during the workshop
- All sources are technically challenging
  - Need to focus on needs of experiments
- Not-yet-predicted or imagined science will take advantage of sources that push the technology to the limits
- We need to consider the needs of multiple users as well as individuals with breakthrough experiments